2012 Annual Report for Project on Isopycnal Transport and Mixing of Tracers by Submesoscale Flows Formed at Wind-Driven Ocean Fronts

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LONG-TERM GOALS

This project is part of the DRI on Scalable Lateral Mixing and Coherent Turbulence that aims to characterize lateral mixing in the ocean on scales of 10m-10 km, the submesoscales. Lateral mixing at the submesoscales is not accounted for in present-day ocean models. This deficiency is a potential source of error in the numerical prediction of the distribution of temperature, salt, nutrients, phytoplankton, pollutants, etc. in the upper ocean. The goal of the DRI is to develop parameterizations for submesoscale processes to improve the simulation of lateral mixing in ocean models.

OBJECTIVES

Winds blowing along ocean fronts are highly effective at energizing flows on the submesoscale. The process involves three stages: a frontal mixing stage where small scale gravitational and symmetric instabilities homogenize properties in the mixed layer, a subduction phase where three-dimensional baroclinic mixed layer instabilities exchange fluid along isopycnal between the mixed layer and pycnocline, and a phase in which the mixed layer instabilities evolve into coherent vortices that drive lateral stirring along surfaces of constant density. Near-inertial waves (NIWs) can be generated as well that are strongly modified by fronts. The objective of this research is to characterize and parameterize the submesoscale physics involved in each of these steps and in the generation, propagation, and dissipation of NIWs, and evaluate the lateral mixing characteristic of the flows. Dynamical insights gained from the research have been used for planning, interpreting, and analyzing observations collected during the two field programs that were conducted as part of the DRI.

APPROACH

The approach taken in this project is to use a combination of theory, process-oriented numerical experiments, and analysis of observations of wind-driven submesoscale flows to study the governing physics of these flows. Analysis and diagnostics of the simulations and observations will be used to construct parameterizations for coarser resolution numerical models that cannot explicitly resolve the submesoscale.

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WORK COMPLETED

In this fourth year of the project I participated in the field experiment conducted in the Gulf Stream during February and March. My role on the ship was to provide theoretical guidance for planning surveys and to supply in near real time preliminary analyses of the data to interpret the observations and adapt our sampling strategies accordingly. The cruise was very successful, yielding a remarkably rich data set of submesoscale phenomena. Many of the preliminary results from the field campaign will be presented at the AGU Fall Meeting this upcoming December in a session "Physics and Biogeochemistry of Submesoscale Processes" that I co-organized with Raffaele Ferrari, Kipp Shearman, and Gualtiero Badin.

In addition to this observational work, I have completed two theoretical studies focused on the interaction of NIWs and ocean fronts. One study, to appear in the Journal of Fluid Mechanics, i.e. Thomas (2012), used an analytical theory to quantify the energy exchange between NIWs and mesoscale eddies at ocean fronts. The second study, i.e. Whitt and Thomas (2012), used both analytical theory and numerical simulations to characterize the modification of the properties, propagation, and energetics of NIWs at fronts.

RESULTS

Four experiments were performed along the North Wall of the Gulf Stream in February and March 2012 from R/V *Atlantis* and R/V *Knorr*. Each experiment was aimed at following a feature of interest, with the ships and gliders following a Lagrangian Float planted in the feature. The features that were sampled shared characteristics of wind-driven submesoscale flows in both the frontal mixing and subduction phases.

Analysis of two Lagrangian drifts conducted during periods of down-front winds revealed evidence of symmetric instability (SI). On both drifts the Lagrangian float cycled vertically through a stratified boundary layer with near zero potential vorticity (PV), see lower panel of Fig. 1. During the first drift the float's vertical circulation was characterized by fast, cross-isopycnal downwelling into the stratified boundary layer followed by slower upwelling along isopycnals, typical of SI as seen in the simulations (Fig 1, top panel). In the second drift the winds were rapidly varying, triggering inertial motions that appeared to play an important role in the PV dynamics and turbulence of the boundary layer. Dye patches released near the float in both drifts revealed rapid lateral dispersion of the dye, consistent with the frontal mixing stage of wind-forced submesoscale flows.

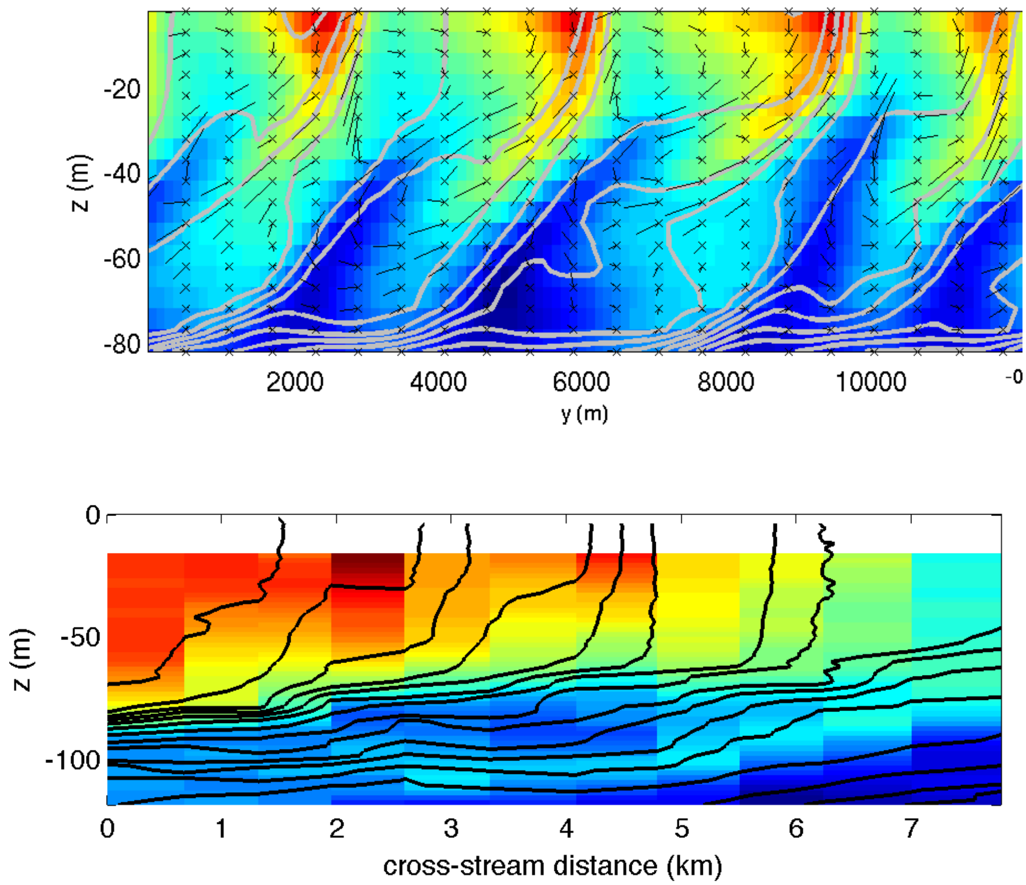

Fig. 1: Down-stream velocity (color) and isopynals (contours) in a numerical simulation of wind-forced symmetric instability (top panel) and the observations from the Gulf Stream collected during the first Lagrangian drift. The cross-stream secondary circulation of SI (vectors) is also shown in the top panel. Both the simulations and the observations are characterized by a stratified, turbulent boundary layer with near zero PV.

Earlier in the cruise, the Lagrangian float was deployed in a weakly stratified layer within the North Wall and on the downstream side of a Gulf Stream meander crest, a region where subduction was anticipated. The float was indeed observed to subduct. Cross-stream sections of velocity, density, and vorticity made following the float reveal that the flow had characteristics similar to an actively developing intrathermocline eddy (ITE) (i.e. Fig. 2), a submesoscale phenomenon that is expected to form at wind-forced fronts during the subduction phase. ITEs are generated at fronts through the process of vortex tilting when horizontal vorticity associated with the vertical shear of the frontal flow is tilted downward by a cross-stream secondary circulation of the right sense. Such a secondary circulation was observed, with downwelling (upwelling) on the denser (lighter) side of the front. At the center of the overturning circulation the vertical vorticity attained its minimum, as would be expected from vortex tilting and ITE formation.

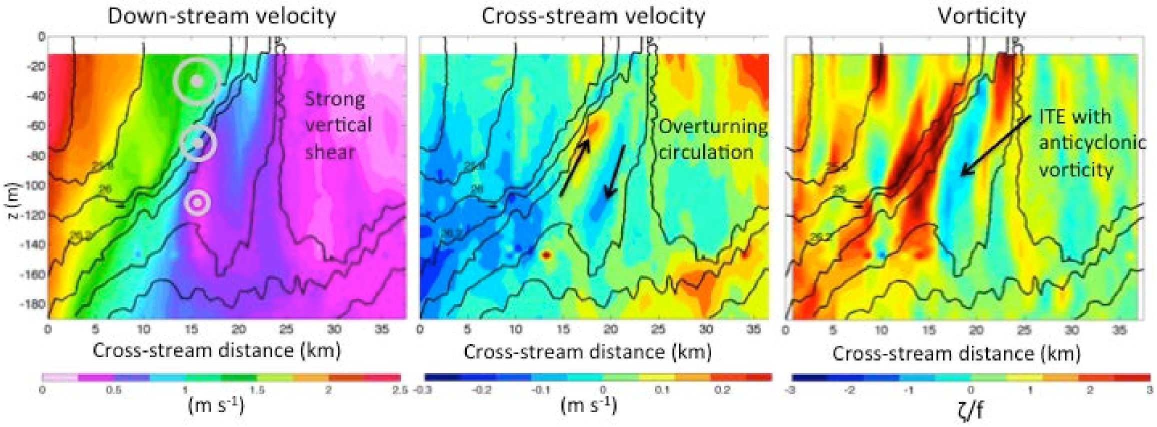

Fig. 2: Observational evidence of the formation of an intrathermocline eddy in the Gulf Stream. The down-stream velocity (left) is strongly sheared in the vertical. The cross-stream (center) was characterized by an overturning circulation that is conducive for the generation of strong anticyclonic vorticity, which was indeed seen in the observed vorticity field (right).

In addition to these balanced motions, there was evidence of strong near-inertial wave activity. Coherent bands of ageostrophic shear characteristic of amplified near-inertial waves were observed below the surface boundary layer in the highly baroclinic North Wall of the Gulf Stream under strong and variable wind forcing (Fig. 3). Lines of constant ageostrophic shear, nearly parallel to slanted isopycnals, propagate upwards with time and show a pronounced peak in energy at near-inertial frequencies. Vertical profiles of the shear show enhanced clockwise over counter-clockwise polarization with depth suggesting predominantly downward energy propagation. The gradient Richardson number, Ri, is also coherently banded and regions of low Ri coincide with maxima in ageostrophic shear. Within these bands there are areas about 1 km wide and 10 m deep where Ri < 1⁄4 and hence the flow is susceptible to shear instability. These features are consistent with a theory of Whitt and Thomas (2012) for near-inertial waves interacting with strongly baroclinic currents, which predicts that the flow, streamlines, and shear of the waves should align with the tilted isopycnals of the current (i.e. Fig. 4). This interaction preconditions the waves for shear instability and, therefore, may enhance mixing diapycnally as well as isopycnally through shear dispersion.

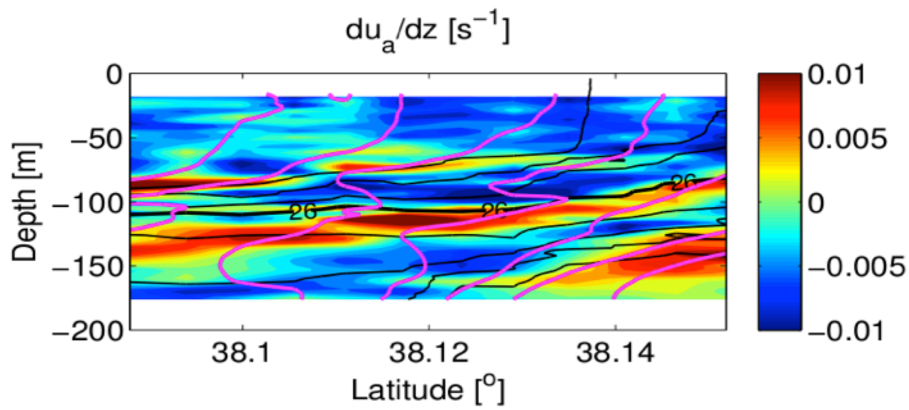

Fig. 3: The ageostrophic shear (colors) observed in the Gulf Stream takes a banded structure characteristic of near-inertial waves interacting with a front, i.e. with lines of constant shear that align with isopycnals (black contours).

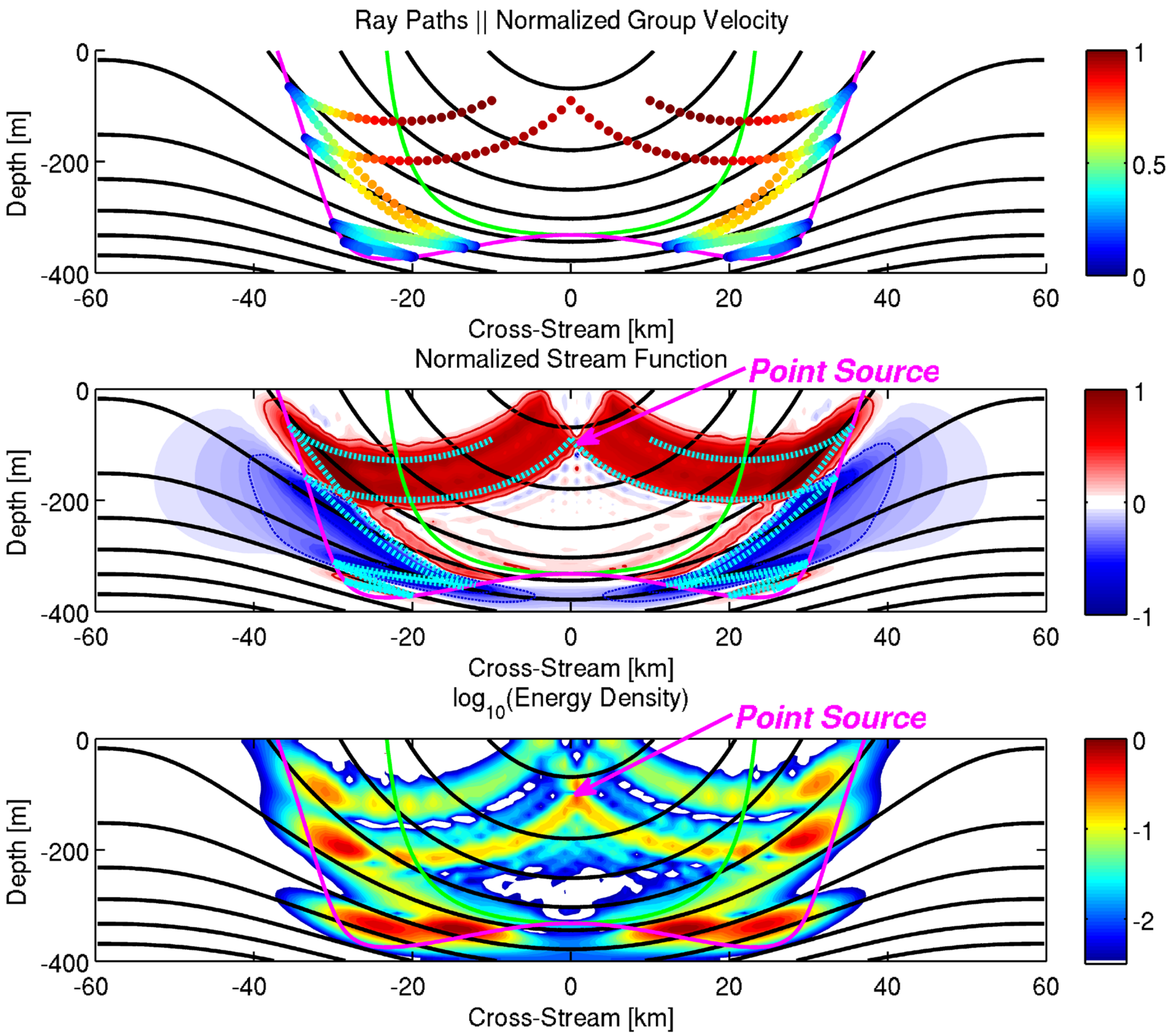

Fig. 4: Numerical solution for the streamfunction (colors) of a near-inertial wave interacting with fronts and forced by an oscillatory point source. Isopycnals are contoured in black. To view an animation of the evolution of the streamfunction and shear visit http://www.youtube.com/watch?v=xltiOXAhs_M&feature=youtu.be

The theory of Whitt and Thomas (2012) is valid for near-inertial waves interacting with a front that is not evolving in time. When the front is actively being intensified by a frontogenetic strain field, driven for example by mesoscale eddies (see Fig. 5), the interaction is modified and leads to a rapid energy exchange between the eddies and the waves (Thomas 2012). In the process, the intensifying vertical shear of the front causes the polarization relation of the near-inertial waves to change, becoming more rectilinear with time (Fig. 5). In doing so, the waves induce a momentum flux that is down-gradient. Thus the waves act as an effective viscosity, mixing the momentum of the eddy flow field and hence extracting kinetic energy (KE) from the eddies. The KE of the waves is ulimately lost however because of the ageostrophic circulation that accompanies frontogenesis. This is because the wave's streamlines tilt with the ageostrophic shear causing the it to lose KE via shear production.

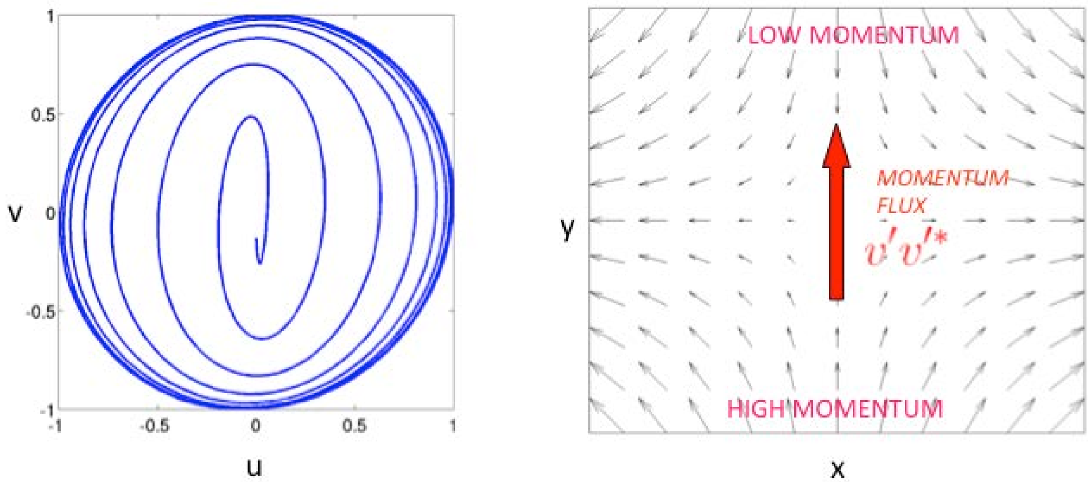

Fig. 5: A hodograph of the velocity of a near-inertial wave in a front undergoing frontogenesis illustrates how the wave experiences a change in polarization relation with time, transitioning from being circularly polarized to rectilinear in the cross-front, y direction. In the process, the wave induces a momentum flux that is down the gradient in momentum associated with the eddy-driven strain field whose velocity is shown in plan view on the right.

IMPACT/APPLICATIONS

The observations of symmetric instability in the Gulf Stream shed light on a new form of turbulence in the upper ocean that we are calling SI-turbulence. It forms at wind-forced fronts and compared to other forms of upper ocean turbulence, such as wind-driven shear instabilities and Langmuir circulations, SI is new and unique in that it derives its energy from fronts as opposed to the wind or waves. It thus represents a sink of energy for the general circulation and is also quite efficient at lateral mixing as evidenced by the rapid dispersion of dye during the surveys. The trapping of strong near-inertial waves at fronts that has been observed in the Gulf Stream and modeled by Whitt and Thomas (2012) also represents an efficient mixing mechanism. In regions of eddy-driven frontogenesis these waves remove KE from eddies while simultaneously loosing their KE to cross-front ageostrophic motions. Given the large amount of KE in near-inertial waves and the ubiquitous combination of eddy-driven strain and fronts in the ocean, it is estimated that this mechanism could play a significant role in the removal of KE from both the internal wave and mesoscale eddy fields.

PUBLICATIONS

Thomas, L. N. (2012), On the effects of frontogenetic strain on symmetric instability and inertia-gravity waves, *J. Fluid Mech*., [in press].

Whitt, D. B., and L. N. Thomas, 2012. Near-inertial waves in strongly baroclinic currents. Part I: Normal incidence, *J. Phys. Oceanogr*.